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Design optimization of a horizontal axis micro wind turbine through development of CFD model and experimentation

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Abstract

The aim of this paper comprises of investigating the viability of using an available indigenous blade as horizontal axis micro wind turbine blade and further improvement of this particular blade performance through design modification and CFD simulation. The focus was to use this blade in the urban areas of Bangladesh where the air speed is not usually high enough to harness wind energy with a micro wind turbine efficaciously. Though it requires a minimum wind speed of around 4.2 m/s to start self-rotation of this available blade without the help of external aid, the optimized design would demand a less air speed as the torque would be increased and this might be successfully used in roadside or housetop applications. Experimental and numerical analyses were conducted with the blade and the design modification and optimization were done with the help of CFD analysis. The experimental and numerical plots showed excellent similitude in qualitative manner. We went through with the optimization of blade design based on the blade pitch angle and subtended angle.

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Keywords: Micro wind turbine; CFD, blade pitch angle; blade subtended angle; co-efficient of power; starting torque, tip speed ratio.

1. Introduction

Wind energy is one of the many renewable energy sources that show a lot of promise and potential. The most conventional way of harnessing energy from wind has been the ‘wind turbines’. One of the main limitations of using conventional wind turbine is the insufficiency of “Minimum wind velocity” to run the wind turbine. Because of this problem, unlike solar energy, wind energy extraction is greatly dependent upon location and is only applied to

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onshore and offshore regions having met the specified minimum wind velocity. Moreover, to efficiently extract power from the wind, the wind turbines are of large size which limits their application only in remote areas. Very high initial cost is also a prime concern which restricts the large scale marketing of such turbines.

Many researcheshave been carried on to develop better wind turbine which can extract power from low velocity wind. The recent addition to this research is “Micro wind turbine”. These small scale turbines are different from their larger counterpart in the fact that they are specially designed to extract power from low velocity wind using comparatively smaller space, thus avoiding the size constraint [1][2][3]. These “micro wind turbines” can be used as Roof-top/residential wind turbine or on the side of the road (Road-side wind turbine) with proper wind energy resource assessment studies [4]. The underlying idea is that, though they individually produce a very small amount of power, their cumulative contribution can add significant amount of power to the grid. In a country like Bangladesh, where wind velocity is not feasible enough to install large scale wind turbines, micro wind turbines can show a lot of potential.

Nomenclature

C_p	Power coefficient	a	axial induction factor
C_t	Torque coefficient	U	initial velocity
T	Thrust	ρ	Density of the fluid
λ	Tip-speed ratio	ω	Angular velocity

2. Methodology

2.1. Selection and Specification of Micro Wind Turbine

The micro wind turbine under investigation is an indigenous blade, which is plastic made, mass produced, very cheap and nationwide available. The blade does not have any airfoil shape, rather it has simple fan-type configuration which is has an advantage of higher power efficiency [5]. The rotor diameter is 236.5 mm which is ideal for a micro wind turbine. The blade pitch angle is the angle at which the wind makes contact with the blade surface. The blade has a pitch angle of 22 degree and blade-subtended angle of 37.74 degree. Later these parameters were varied in the optimization process. The blade twist angle was considered negligible and was not taken into account. The number of the blade was three. In the experimentation and numerical analysis, this number was not changed to keep the solidity of the turbine fixed throughout.

2.2. Governing Equations

Let us consider a cylinder of air to calculate the power in the wind which is often referred to as a stream tube. The stream tube travels towards the wind turbine rotor, with an initial velocity U and slows to U_1 (due to pressure changes) by the time it reaches the rotor. The rotor captures some of the energy so that air flowing out behind it moves even more slowly, at a velocity U_2, but the same amount (mass) of air coming towards the rotor also leaves behind the rotor.

Because linear momentum is always conserved, a force must act on the wind to make it slow down. From Newton’s third law, this force on the wind is equal to and opposite to the thrust, T, the force of the wind on the turbine. The thrust force comes from a change in pressure as the wind passes the rotor and slows down. Conservation of linear momentum dictates that the thrust must be equal and opposite tothe change in momentum [6].

$$T = \frac{dm}{dt}(U - U_2) = U(\rho A U) - U_2(\rho A U)_2 = \frac{1}{2}\rho A(U^2 - U_2^2) \tag{1}$$

Further algebra shows that the power extracted from the air is,

$$P = \frac{1}{2}\rho A U^3 \times 4a(1-a)^2 \tag{2}$$

Where a new value, the axial induction factor a, has been defined as

$$a \equiv (U - U_1)/U \tag{3}$$

The fractional decrease in the wind velocity once it has reached the rotor, due to a change in pressure (depending on how much energy the rotor captured to slow the wind). We can define a ‘performance power coefficient’, C_p, as the ratio of the power in the rotor to the power in the wind:

$$C_p = 4a(1-a)^2 \tag{4}$$

The power coefficient indicates the efficiency of the turbine based solely on the stream tube concept, without accounting for non-ideal conditions and inevitable losses from the blades, the mechanics, and the electronics.Taking the derivative of the power coefficient with respect to “a” and setting it equal to zero sets forth a restriction that no HAWT can extract more than 59% of the raw kinetic power in the wind which is known at Betz’s Limit.

Tip-speed ratio, λ is defined as the ratio of blade-tip speed to the wind speed. If the radius of blade is R, angular velocity is ω and wind speed is v then,

$$\lambda = \frac{\omega R}{v} \tag{5}$$

2.3. Model Design and CFD Simulation

The entire 3D micro wind turbine model was designed in computer as per the actual dimensions. For optimization purpose, these dimensions were later changed to obtain the optimization curves. For CFD simulation, Favre-averaged Navier-Stokes equations were used. The Flow Simulation employs k-ε model.

The rectangular computational domain was constructed which enclosed the solid body and has the boundary planes orthogonal to the specified axes of the Cartesian Co-ordinate system. Computational Mesh was constructed in several stages. Narrow channel refinements were done and locally refined rectangular computational mesh was obtained. For computational analysis, the initial mesh level was set to 5 to support computer memory configuration. Refinement level and criterion were set at level 1 and 1.5 respectively. Unrefinement criterion was set to 0.15. Adaptive refinement in fluid was selected and approximate maximum cells were 10400000. Tabular refinement was chosen with relaxation interval of 0.2. External Analysis Type was specified which excludes closed cavities without flow conditions and internal spaces. Working fluid was set to air with atmospheric pressure and temperature. The blade wall was assumed to be adiabatic and surface roughness was not considered. The CFD model after mesh generation and simulation are shown below:

a

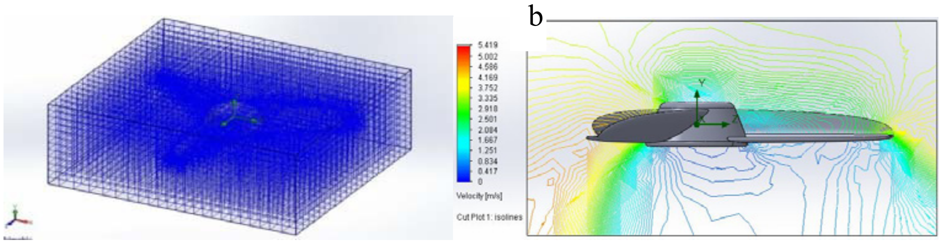

Fig.1.(a) Model after mesh generation (trimetric view); (b) Velocity contours after simulation (isolines).

2.4. Experimentation and Model Validation

To validate the result of numerical computation, the CFD model was subjected to wind tunnel experimentation.

The turbine generated EMF and current output was measured using a Multimeter. The blade rotational velocity was measured in RPM using a photo sensor tachometer. The air velocity was measured using an anemometer. For power output, the turbine was connected to a motor acting as a generator in this case. In Fig.2, the setup is shown. The wind tunnel's air velocity was changed to different values to obtain different power output and turbine blade rotation. Air velocity was not taken above 7 m/s, as it was not necessary.

Fig.2. The wind turbine setup.

2.5. Optimization

The torque produced and the coefficient of performance depends on different blade parameters. Among them, blade subtended angle and blade pitch angle were considered for optimization. The optimization procedure was carried out numerically to enhance the blade performance by increasing Power coefficient (C_p) and Torque Coefficient (C_t),as maximizing C_p ensures higher power extraction[7]. The blade subtended angle and pitch angle were varied gradually at a specific wind velocity to obtain different torque output. Graphs were plotted with these data and the parameters producing the highest torque were sought out. Further analysis is given in later sections.

3. Results

3.1. Experimental and Numerical Results

Table 1 represents all the experimental and numerical data used for model validation. The experimental output was Electrical Power whereas the numerical output was the Torque.

Table 1.Experimental and Numerical Data for Model Validation

Air speed (mps)	N rpm	Voltage, V (v)	Current, I (amp)	Electrical power (watt)	Power available (watt)	Maximum Obtainable power(watt)	Torque, T (N-m)	Mechanical power (watt)
2.5	390	0.67	0.08	0.0536	0.412	0.244	0.00136	0.0555
3.1	650	0.79	0.17	0.1343	0.785	0.465	0.00206	0.1403
3.5	850	1.11	0.21	0.2331	1.130	0.670	0.00288	0.2564
4.2	1425	1.52	0.29	0.4410	1.953	1.157	0.00340	0.5074
4.5	1545	1.63	0.33	0.5380	2.403	1.424	0.00399	0.6456
5.0	1720	1.78	0.36	0.6410	3.296	1.953	0.00438	0.7889
5.5	1900	1.99	0.42	0.8360	4.387	2.580	0.00513	1.0207
5.7	2025	2.16	0.47	1.0150	4.883	2.894	0.00589	1.2490
6.0	2215	2.33	0.52	1.2120	5.695	3.375	0.00648	1.5031
7.0	2910	2.62	0.62	1.6240	9.043	5.359	0.00666	2.0295

Figure 3(a) depicts the comparison of the CFD and experimental results on the relationship between power output and angular velocity. The power output could be estimated by multiplying the angular velocity of the turbine with the torque captured by the turbine when it was rotating at that angular velocity. This is very lucid from the figure that the experimental data well match with the numerical analysis. They both show non-linearity but increase in power output with the increase in angular velocity.

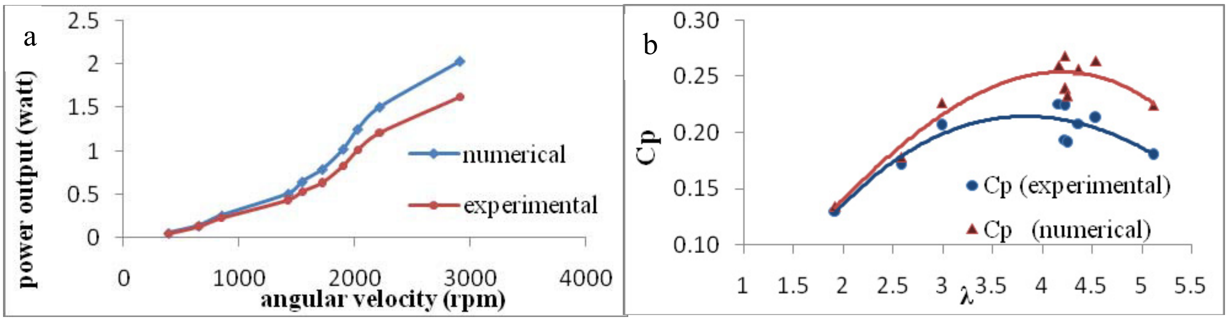

Fig.3.(a) Power output vs. angular velocity; (b) Power Coefficient vs. Tip speed ratio.

Figure 3(b) bears witness to the relationship between power co-efficient (C_p) and tip speed ratio (λ). There is significant and qualitative similarity between the experimental and numerical bell-shaped curves.

3.2. Optimization Result

We changed the blade pitch angle and subtended angle to make changes in the torque output. The larger the torque develops, the greater the power output as torque multiplied by the rpm begets power. We gradually had changed the blade pitch angle and subtended angle to have different torque and for every angle respective torque output was taken down.

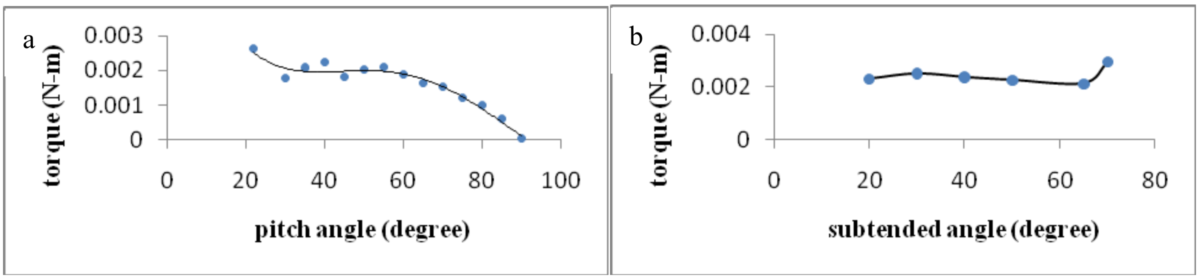

Fig.4.(a) Torque vs. Pitch angle at wind speed of 3.5 m/s; (b) Torque vs. Subtended angle at wind speed of 3.5 m/s.

Figure 4.(a) shows a change in torque output with the change in blade pitch angle. The torque output is calculated numerically for 14 different blade pitch angles at fixed wind velocity of 3.5 m/s. The curve indicates a rough inverse relation between torque output and pitch angle. The maximum torque output is obtained at 22 degree of blade pitch angle. Figure 4.(b) represents a torque output vs. blade subtended angle curve, where the torque is calculated numerically for 6 different blade subtended angles at 3.5 m/s wind velocity. The curve remains almost parallel to the x axis but suddenly increases at the end, providing the maximum torque at blade subtended angle of 70 degree.

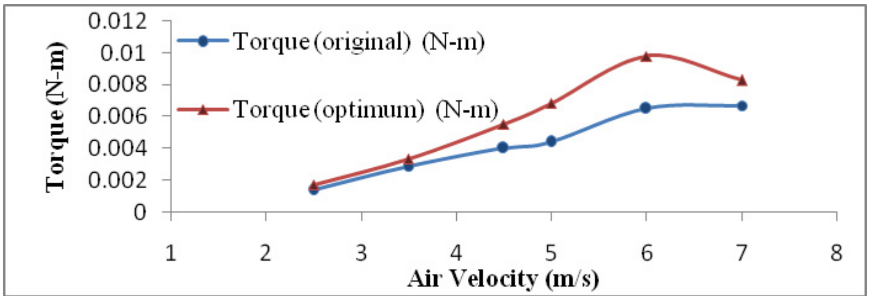

Fig. 5. Torque vs. Air velocity.

Figure 5 represents a Torque vs. Air velocity graph where the curves of numerical simulation results of both original blade and recommended optimized blade are illustrated. The optimized numerical analysis was carried out with blade pitch angle of 22 degree and blade subtended angle of 70 degree for different wind velocities. From this graph, it is evident that the optimized result shows a significant improvement of torque.The optimized design also improves the starting torque characteristics. The starting torque required for this specific design of blade is only available at wind velocity of 4.2 m/s, which is confirmed experimentally. From Figure 5, this starting torque can be attained by the optimized turbine blade at wind velocity of 3.5 m/s, which enables it to operate independently at even lower wind velocity regions. The solidity of the blade was kept unchanged. At lower tip speed ratios, increasing solidity may further increase the turbine's power take-off relative to the lower solidity device[8].

4. Conclusion

This investigation aims at validating the CFD model with the experimental setup and afterwards optimizing the blade geometry numerically for better performance. The CFD simulation corresponds qualitatively to the experimental data. The numerical optimization, which was carried out considering the blade pitch angle and blade subtended angle, shows a better torque output and subsequently a better power output and starting torque. A low blade pitch angle of 22 degree and high blade subtended angle of 70 degree showed maximum torque output for this type of blades. There was a maximum increase in torque of about 55% at the air velocity of 6 m/s.

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